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Increasing the insulation properties of filter respirators to protect miners' respiratory organs from dust

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Abstract

To increase the insulating properties of elastomeric half-masks, it is suggested to perforate the obturator in the area of the nasal bridge, chin and cheeks, which allows for adjustment in its size, thus preventing the occurrence of wrinkles on the user's face in the areas which are the individual features of a particular user's face. Three versions of the perforated filter respirator obturator have been proposed: in the first, the holes are made along the entire perimeter of the obturator; in the second, the holes are only in the area of the cheeks and nasal bridge; in the third, incisions with a diameter of 5 mm are made in the area of the nasal bridge and cheeks. The result of modelling a set of alternative solutions taking into account the coefficient of protection of filter respirator half-masks, the distribution of compressive forces, which are determined in the environment of the packages "ANSYS" and "Solid works", has been obtained on the basis of main indicators of the proposed models. To make a decision on choosing the best model, the mass of the elastomeric half mask, its dimensions and the complexity of the design were additionally considered. On the basis of expert evaluation, according to the described procedure for determining the utility function of the factors from their values, it has been defined that the second model of the half-mask is characterized by the best parameters. Conducted laboratory studies to determine the aerosol absorption coefficient by the obturation line showed the lowest indicator in the second option.

Keywords:

Dustiness of the working space; occupational disease; filtering respirator; anthropometric parameters of the face; parameters of the respirator

1. Introduction

The mining industry remains the most dangerous in the world, especially with underground mining. This is evidenced by the results of studies that are presented in the works of many scientists (**Wei-ci et al., 2011; Akgün, 2015; Amponsah-Tawiah et al., 2016; Verma et al., 2017; Ajith et al., 2020; Ivaz et al., 2021; Nehrii, Volkov et al., 2022; Nehrii, Glyva et al., 2022**). The occupational safety of miners depends on their working conditions, which are characterized by the factors of the production environment and labor process: difficulty of work, dustiness of the air, lighting, production noise, vibration, microclimate, and several other factors, depending on the ore, including high radon exposure. These factors are not only harmful and dangerous for the health and life of workers, but there is also the fact that masks distract and affect the working capacity of miners (**Nehrii, Volkov et al., 2022**).

With the whole variety of risk factors for miners' injury and their acquisition of occupational diseases, air dustiness is one of the highest priority factors that must be taken into account when planning labor protection measures and improving the working conditions of miners (**Nehrii, Glyva et al., 2022**).

The content of dust in the mine atmosphere is also a factor complicating working conditions and a source of occupational diseases associated with respiratory diseases. The dust content of the working space can be an obstacle in assessing the situation at the workplace, as it

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limits the possibility of receiving warning and emergency signals (**Nehrii, Glyva et al., 2022**). The only way to solve the problems of creating standardized working conditions at workplaces is the introduction of energy- and resource-saving technologies that ensure the optimization of labor protection and safety costs by localizing dust emissions at the places of formation and exhausting dusty air using built-in devices adapted to working tools, as well as subsequent dust collection in sanitary air purification equipment (**Strzemecka et al., 2019**; **Klishch et al., 2021)**. The introduction of such measures requires significant costs for the reconstruction of technological equipment and the purchase of sanitary air purification units. There is also a need to improve the effectiveness of the protection of workers through the use of personal respiratory protection. Despite the fact that in the hierarchy of precautionary measures, these agents rank last due to their low efficiency, they sometimes remain the only protective barrier that keeps workers from getting occupational diseases. Therefore, the issues of improving designs or developing new means of individual respiratory protection are quite relevant. This will significantly increase the level of protection for workers, while providing a comfortable feeling as the basis for continuous use.

The main problem of ensuring reliable protection of the respiratory organs from a harmful environment is the different anthropometry of faces, changes in facial expressions during a conversation and various movements (**Cheberiachko et al., 2022**). It is the anthropometric parameters of the user's face that have a significant impact on the insulating properties of personal respiratory protection equipment. It is believed that the most problematic place, where gaps along the obturation line of a filtering respirator are most often fixed, is the area of the nose (**Bazaluk et al., 2021**). Analysis of the data shows that about 84% of the gaps were found in the area of nasal bridge (near the nose and cheeks), and 73% of the gaps are slit-shaped (**Bhattacharyya et al., 2006**). In addition, the relationship between the user's face parameters and the placement of the gaps has been recorded (**Cheberiachko et al., 2020**).

The conducted research helped manufacturers to improve the protective properties of filtering respirators and develop various seal designs. For example, one of the effective ways to solve this issue is to manufacture half-masks of a filtering respirator with a special frame, which, by changing its geometry, will retain the given shape of the front part of various types of users' faces and a sufficient area of the obturation line during conversations and head movements (**Cai et al., 2018**). Also, to increase the tightness of the half-mask to the user's face, the obturator of the filtering respirator in the area of nasal bridge is fully or partially reinforced with an additional sealant made of polyurethane foam, soft rubber or silicone (**Kwon et al., 2022**). Most manufacturers use a nose clip to reduce suction, especially around the nasal bridge. In the case of half-masks of a filtering respirator with an airtight facepiece, the reliability of isolation depends on the design of the obturator and the material it is made of. The following seals between the half-mask and the face are known: "single-skin respirator seal" (normal, single fold), "airbag" (inflatable obturator), "reflex" (flexible U-shaped fold providing two contact strips) and "double-bladed respirator seal» (corrugated obturator with two strips touching the face) (**Caggiari et al., 2016; Chopra et al., 2021; O'Kelly et al., 2022**). The best one is the last one. The double seal ensures that the respirator fits better to the face than other designs, at least due to the greater face contact area (**Wetherell et al., 2001; Wardhan et al., 2019**). However, such a design significantly reduces the internal space of the half-mask and is therefore used only in special cases, for example, in military gas masks. At the same time, the search for ways to improve the insulating characteristics of the filter respirator is still underway.

It is believed that the effective protection of workers from pollutants will be provided if three main conditions are met (**Stemen et al., 2021**):

- the use of a high-quality filter element with low breathing resistance and high dust capacity, taking into account the main patterns of accumulation of dust sediment with a changing filtration rate (**Jung et al., 2020**; **Mauricio da Costa Ramos et al., 2022**);
- increasing the reliability of isolation of respiratory organs from the environment by improving the obturation line of half-masks of filtering respirators, fastening elements of half-masks on the head of workers (**Vinothkumar et al., 2017; Lowney et al., 2018; Tarfaoui et al., 2020; Akagi et al., 2021; Kamaluddin et al., 2022**), timely and correct use of personal respiratory protection equipment during the entire period of operation, when the dust content exceeds the maximum allowable concentration, and by determining the safe area of their use and proper selection procedures (**Shaffer et al., 2015; Wu et al., 2017**).

There are some main reasons for the deterioration of the respiratory protection of workers using filtering respirators: poor quality filter, low isolating properties and unwillingness to timely and constantly use a respirator. Most questions arise about the reluctance to use a respirator, since this reason is associated with a feeling of discomfort (**Shenal et al., 2012**) due to an uncomfortable seal and tissue deterioration and bruising at the points of contact with the face (**Cloet et al., 2022**). That is, the refusal to use a half mask occurs due to the imperfection of the sealing structure. But many cases of respirator deterioration have been documented when workers move their heads, talk, or when there is insufficient downforce (**Krishnan et al., 1994**; **Myers et al., 1988**). The distribution of aerosol leaks along the obturator strip has been determined in studies (**Oestenstad et al., 1990**; **Chopra et al., 2021**). The most problematic areas of compaction are considered to be the bridge of the nose, where leakage is 58% of all recorded cases, while near the chin it is

18%, near the cheeks - 15%, near the mouth - 6%, and under the lower jaw - 3%. All of this points to the need to eliminate the causes of inefficient use of respirators.

Under the above conditions, the protective properties are most affected by the insulating characteristics of half-masks of filtering respirators, since it is they that make it possible to ensure that the obturator profile matches the anthropometry of the face and create comfortable conditions for use so that there is no desire to remove the filtering respirator in hazardous working environments. For miners, this issue is relevant because they spend most of their working time in filter respirators, in particular, in "Shakhtar" respirators, which are made of modified rubber (**Oestenstad, Zwissler, 1991**).

The aim of the research is to improve the design of the half-mask of the "Shakhtar" filter respirator to improve its insulating properties.

2. Methods

To search for a design solution to improve the insulating properties of the half-mask of a filtering respirator, the method of parametric synthesis has been used, which made it possible to determine the most acceptable model from several proposed ones. To do this, we generate many alternative solutions to improve the design of the filter respirator half-mask, based on several proposed solutions. As a result, we get a number of options (M_1, M_2, ..., M_n) which can satisfy the conditions of our research. Further, for each of the alternative proposed options, we form a mathematical model, where we set the limits for changing the design indicators of the quality of personal respiratory protection equipment (protection coefficient, suction coefficient, breathing resistance), criterial and functional restrictions (head tension force, specific pressure on the face of the user). Then, using the known methods of revising statistical laboratory tests, we check the set of feasible solutions (D_1), and select effective (Pareto-rational) variants of the first alternative structure (M_1). If the set D_1 is empty, then, correcting the constraints, we carry out a parametric synthesis of M_1- structure to obtain at least one effective solution.

To form a set of alternative Pareto-rational variants of the proposed models, we sequentially solve the vector optimization problem (**Bulat et al., 2020**). To do this, we use **Equations 1** and **2**:

$$f_i(x) \to \min_x; \; x \in D \; \left(i = \overline{1,k}\right); \tag{1}$$

$$D = \left\{ x \in R^n \; g_i(x) \le 0; \; g_i(x) = 0 \; \left(i = \overline{1,m}\right); \right.$$
$$\left. \left(i = \overline{m+1,s}\right); \; a_j \le x_j \le b_j \; \left(j = \overline{1,q}\right) \right\} \tag{2}$$

Where:

x – a design parameter vector ($x \in R^n$);

D – a set of feasible solutions;

$f(x)$ – scalar target function of a vector argument;

$g(x)$ – scalar functions of a vector argument.

The solution of the problem according to **Equation 1** is carried out in three stages:

1. Using the method of laboratory tests or $L_{\pi\tau}$ - sequences, we set N test points $x^1, x^2, ..., x^N$, uniformly located in a given area of the optimization parameter space. At each point x^i, we check the fulfillment of all functional constraints. If they are not fulfilled at any of the given points, then we do not take them into account in further calculations. We calculate the value of all partial quality criteria $F_j(x^i)$, where j = 1, 2, ..., k for the selected points x^i.
2. After viewing the points that belong to the range of acceptable values, based on the results of the calculations of the values of partial criteria, we assign criterial constraints.
3. We check the non-emptiness of the range of admissible solutions. Among the options that satisfy the accepted criterial constraints, we choose the options that satisfy all partial criteria. If:
   - such points x^i exist in the parameter space (at least one), we remember the value of the design parameters and quality criteria, and include these options as components of the set of alternative Pareto-rational options for the considered models of respirators;
   - such options are not found; we return to the second stage and look at the given criterial constraints;
   - this is impossible, we increase the number of test points N and proceed to the first stage;
   - as a result of increasing test points and changing criterial restrictions, it is not possible to find at least one acceptable option that falls into the area of admissible solutions, this means that the design solution considered at this stage cannot further satisfy the synthesis conditions at the level of design parameters, and it should be removed from consideration.

Similarly, we carry out a multicriteria optimization parametric synthesis of models of half-masks filtering respirators of other alternative structures, select effective solutions from the range of feasible solutions and include them in the set of alternative Pareto-rational options.

The choice of the best of the alternative options is carried out on the main provisions of the theory of total utility, the theory of games and economic behavior, fuzzy sets and the method of expert assessments, characterizing each of the alternative Pareto-rational options by a generalized criterion of utility.

Each half-mask model S_j operating in the q mode is associated with an n-dimensional vector (**Cheberiachko et al., 2022**) by **Equation 3**:

$$x_{qi}^j = \left(x_{q1}^j, \; x_{q2}^j, \; \ldots, x_{qn}^j\right) \tag{3}$$

Where x^j_{qi} is the value of the i^{th} factor for the j^{th} version of the half-mask when operating in the q^{th} mode.

In the above case, we evaluate the models of the half-mask of a filtering respirator by geometric parameters, the tension force of the headband, the protection factor of the filtering respirator, the suction coefficient and the specific pressure of the half-mask.

Taking into account all modes of operation, for each variant S_j we compose a $k \times n$-matrix of factor values by **Equation 4**:

$$A_j = x_{qi}^j \quad (j = 1,2,...,m;\ q = 1,2,...,k;\ i = 1,2,...,n) \quad (4)$$

We consider the matrix A_j as a collection of multidimensional alternatives. Denoting the value of the utility function of the j^{th} alternative S_j as $u(Sj)$ and relying on the main provisions of the theory of total utility, we represent it as **Equation 5**:

$$u(S_j) = \sum_{q=1}^{k} \sum_{i=1}^{n} r_q w_{qi}^j v_i \quad (5)$$

Where:

- r_q – weighting coefficient of the given index of the half-mask (q = 1, 2, …, k);
- w_{qi}^j – the value of the utility function that corresponds to the value (j = 1, 2, …, m; q = 1, 2, …, k; i = 1, 2, …, n);
- v_i – weight coefficient of the i^{th} factor (i = 1, 2, …, n).

Equation 5 is conveniently presented in matrix form by **Equation 6**:

$$u(S_j) = R \times W_j \times V \quad (6)$$

Where:

- $R_j = \|r_q\| - k$ – dimensional string of weight coefficients of a given half-mask index;
- $W_j = \|w_{qi}^j\| k \times n$ – utility matrix corresponding to the matrix $\|x_{qi}^j\|$;
- $V = \|v_i\| - n$ – n-dimensional column of weight coefficients of factors.

So, based on the foregoing, the algorithm for choosing the optimal variant of the filter respirator half-mask model according to technical quality criteria can be represented as a sequence of the following procedures:

1. A matrix of factors is formed $A_j = \|x_{qi}^j\|$.

2. According to the results of expert assessments, each matrix A_j is associated with the factor utility matrix $W_j = \|w_{qi}^j\|$, a column vector of weight coefficients of factors is determined $V = \|v_i\|$.

3. For each alternative S_j, formulas (5) or (6) determine the value of the total utility function $u(S_j)$.

4. The most preferred option (structure and ratio of design parameters) S^* is determined, which satisfies the condition:

$$u(S^*) = max\ u(S_j), \quad (7)$$

After that, using **Equations 6** and **7**, for each alternative model, we determine the average value of the quality criterion and variance estimates. The results of expert assessments of the quality criteria are used to construct curves of the dependence of the utility function of the criterion on this criterion at a given point in the space of design parameters of half-masks. To do this, we present all the quality criteria in one measurement scale from 0 to 1. We believe that with a ratio of design parameters at which the quality criterion received the maximum average value of the expert assessment, its utility function is equal to 1, if the minimum is then 0. Such an assessment entirely corresponds with the basic concepts of the fuzzy set theory (**Alpert, 2020**).

To determine intermediate points and approximate their curve, the methods of half division and expert assessments are used (**Olizarenko et al., 2018**; **Balan, 2021**). At the same time, we ask the experts the question: "For what value of the quality criterion, in their opinion, the utility function of this criterion has a value equal to 0.5." Having worked through the results of expert assessments, we obtain the third point in the rectangular coordinate system "the utility function of the criterion – the value of the criterion".

The ANSYS and SOLIDWORKS software packages were used to model the distribution of air flows through the respirator filter, as well as through the leakage along the half-mask contact band. The Process Models Using System Identification Toolbox method in the MATLAB application package was used to process the experimental data and construct approximation curves for the distribution of the filtration rate over the diameter of the filter.

3. Results and Discussion

Experimental verification of the insulating properties of the samples of the filtering respirator was carried out on humans with a test aerosol. For this, six volunteers were selected in accordance with **Table 1**.

Table 1: Distribution of people under the test by face size

Face height ranges, mm	Standard face width, mm (Bazaluk et al., 2021)		
	129-139 (1 zone)	140-145 (2 zone)	146-155 (3 zone)
136-126	-	2nd test man	5th test man
125-116	1st test man	3rd test man	6th test man
115-105	-	4th test man	-

The test people were familiarized with the manufacturer's instructions for the correct donning of the filtering respirator half-mask and adjusting the fastening of the half-mask.

For a laboratory study to determine the isolation coefficient of the developed model of a half-mask filtering respirator, a test procedure has been carried out, including the determination, in accordance with the requirements EN 140:1998 "Respiratory protective devices — Half-masks and quarter-masks — Requirements, testing, marking" of the coefficients of penetration and suction of the half-mask of a filtering respirator by test aerosol (sodium chloride) on test volunteers.

The value of the coefficient of penetration of the half-mask of a filtering respirator (C_p, %) has been calculated

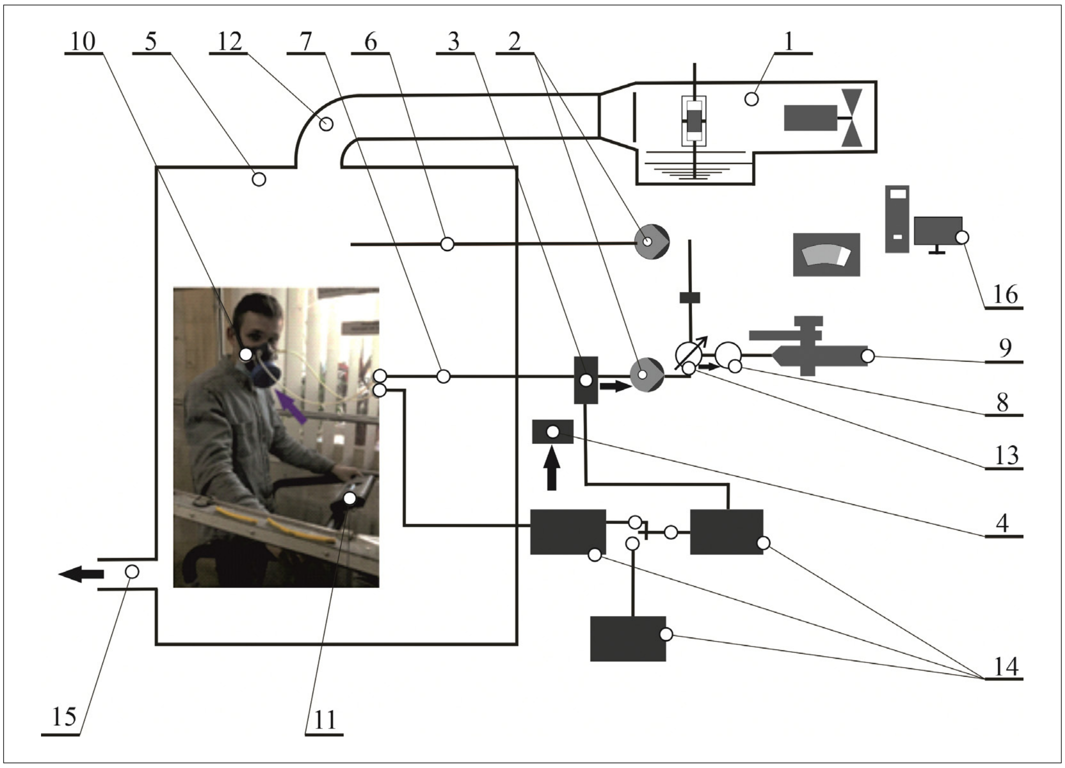

Figure 1: Stand for measuring the penetration coefficient on the tester: 1 - aerosol generator with compressor and aerosol line; 2 –aspirator; 3 - multiway valve; 4 - particulate filter; 5 - a test chamber into which the aerosol enters from above; 6 - chamber air sampler; 7 - submask air sampler; 8 - pressure sensor; 9 – spectrophotometer; 10 – filter respirator; 11 - treadmill located in the test chamber; 12 - air duct and air distributor; 13 - clean air intake pipe; 14 - inspiratory-expiratory phase distribution system; 15 - exhaust ventilation; 16 – PC

according to the results of measurements of the external and submask concentrations of the test aerosol, as (**Holinko et al., 2016; Glass et al., 2022**) in **Equation 8**:

$$C_p = \frac{C_1}{C_0} 100\% \tag{8}$$

Where:

- C_1 – concentration of the test aerosol in the submask space of the filtering respirator, mg/m^3;
- C_0 – external concentration (in the test chamber) of the test aerosol, mg/m^3.

The suction coefficient (C_{suc}, %) for the obturation line has been determined as the difference between the penetration coefficients of the half-mask and the filter of the respirator (**Bazaluk et al., 2021**) by **Equation 9**:

$$C_{suc} = C_p - C_{pf} \tag{9}$$

Where C_{pf} is a coefficient of penetration of the test aerosol through the filter, % (is determined similarly to the C_p by **Equation 7**).

The stand for determining the protective effectiveness of respirators on humans meets the requirements of USS EN 149:2003 "Personal respiratory protection equipment. Filter half-masks. Requirements, testing, marking". The scheme and general view of the installation are presented respectively in **Figure 1**.

During the study, the volunteers sequentially performed various actions (exercises) simulating produc-

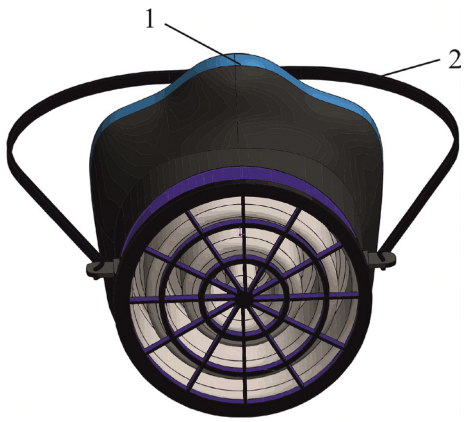

Figure 2: General view of the filter respirator model "Shakhtar": 1 - elastomeric half-mask; 2 - main fitting

tion activities for 2 minutes, namely: normal breathing, deep breathing, turning the head from side to side, moving the head up and down, speaking out loud, walking on a treadmill at a speed of 6 km/h and torso bending. The concentration of the test aerosol (sodium chloride) in the chamber and in the submask space of the half-mask of the filtering respirator was determined using a "Selmi S-115E" spectrophotometer. In the test chamber it was 8...10 mg/m^3. The particle distribution ranged from 0.02 to 2 µm with a mass average diameter of ≈ 0.6 µm.

To measure the concentration under the mask, both samplers indicated in **Figure 2** were used at the same

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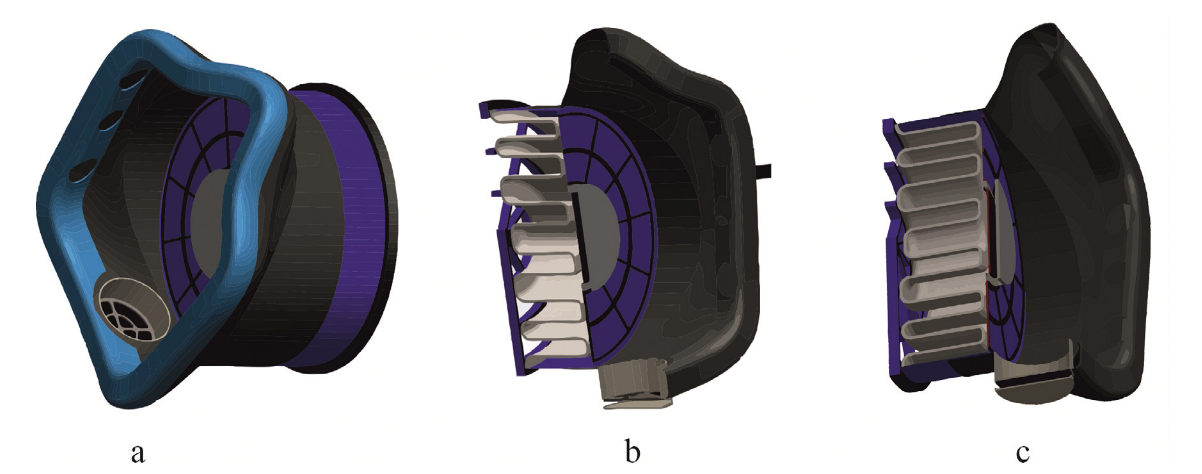

Figure 3: Suggested models for improving the design of the obturator filter respirator: a) with holes around the perimeter of the obturator; b) holes are made at the nasal bridge and cheeks; c) cutouts are made behind the perimeter of the obturator

time, and in the chamber – an additional one, located at the level of the tester's face. The rate of aspiration of aerosols in both cases was 15 dm^3/min. The result was averaged, entered into the table of the specialized program "AAS-2009", which was attached to the spectrophotometer, and displayed on the computer monitor in the form of graphs.

First, the coefficient of penetration of the half-mask worn by the tester without special measures for compacting it along the obturation line was determined. Then – the penetration coefficient of the test aerosol was determined, but only through the filter. At the same time, to prevent suction of the test aerosol behind the obturation line of the half-mask, the places of contact between the face and the obturator were sealed by applying the "Aqualaser" medical gel to the skin of the face. After that, the suction coefficient was determined by **Equation 2**.

Results of theoretical studies. In order to improve the insulating properties, we will consider three variants of different models of the elastomeric half-mask of the filtering respirator of the "Shakhtar" model (see **Figure 2**). The filtering respirator of the "Shakhtar" model is characterized by improved performance properties and an extended period of protective action compared to other filtering respirators used in coal mines (**Knobloch et al., 2023**). It contains an elastomeric half-mask made of airtight material, which is equipped with two exhalation valves located on both sides of the half-mask, a filter cartridge equipped with an additional pleated filter located in front of the main one, as well as an obturator and a mounting set (**Ennan et al., 2006**).

The main disadvantage of the above-mentioned filtering respirator is the relatively high coefficient of unfiltered air suction, which is due to the presence of leaks that form between the surface of the user's face and the half-mask along the obturation line due to various anthropometric parameters of the user's face. This is difficult to take into account when using a half-mask of the same size when just one standard size of a filtering respirator is manufactured. In addition, this filter respirator is characterized by low operational properties associated with uncomfortable (pain) sensations at the place where the half-mask is pressed against the user's face. This is due to an attempt to reduce the amount of suction by increasing the tension of the head bands when fitting the half-mask to the face.

To eliminate this drawback, it is proposed to perforate the obturator of the elastomeric half-mask of the filtering respirator in the area of the nasal bridge, chin and cheeks, which will allow for an adjustment in its size, thus preventing the occurrence of the folds on the face in those places that are inherent in the individual characteristics of a particular user's face. However, as a result, the problem arose of determining the size of the holes in the obturator and their locations. Three options were proposed. In the first one, holes were made around the entire perimeter of the obturator (see **Figure 3a**), in the second, holes were made only in the area of the cheeks and nasal bridge (see **Figure 3b**), and in the third, cutouts with a diameter of 5 mm were made in the area of the nasal bridge and cheeks (see **Figure 3c**).

It is necessary to choose one of the three models, which are characterized by the geometric parameters r_{AB}, r_{AC}, r_{AD1}, r_{AD2}, α_1, α_5 so that for a given head tension force (5-7 N) and variable hole diameter D_1 behind the obturation line, the distance between the holes D_2 and the number of holes V, the isolation coefficient of the half-mask of the filtering respirator has a maximum value. In this case, the specific pressure of the half-mask on the user's face must be within certain limits and not create an additional load.

For theoretical modelling of the distribution of pressing forces behind the obturation line, a system of equa-

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tions has been compiled that describes the limit state of equilibrium of the half-mask on the face (see **Figure 4**) (**Cheberiachko et al., 2022**) by **Equation 10**:

$$\begin{cases} \sum M_A = 0;\; R_B r_{AB} + R_C r_{AC} + F r_{AD} sin\Theta - \\ -G_1 r_{AC_1} \cos\alpha_4 - G_2 r_{AC_2} \cos\alpha_2 = 0; \\ \sum F_{ix} = 0;\; -F_C \cos\alpha_1 - R_C \sin\sin\alpha_1 + \\ +Fcos(\Theta+\alpha_3) + F_B \cos\alpha_5 - R_B \sin\alpha_5 = 0 \\ \sum F_{iy} = 0;\; -F_C \sin\alpha_1 + R_C \cos\alpha_1 + Fsin(\Theta+\alpha_3) + \\ +F_B \sin\alpha_5 + R_B \cos\alpha_5 - G_1 - G_2 = 0 \end{cases} \qquad (10)$$

Where:

- G_1, G_2 – gravity forces of the half-mask and filter, N;
- F – head tension force, N;
- F_B, F_C – friction forces between the half-mask and the face, N;
- R_B, R_C – reactions around the nasal bridge and chin, N;
- α, θ – the angles of inclination of reactions in the area of the nasal bridge and chin with respect to the coordinate system, the initial point of which is in the center of the half-mask filter.

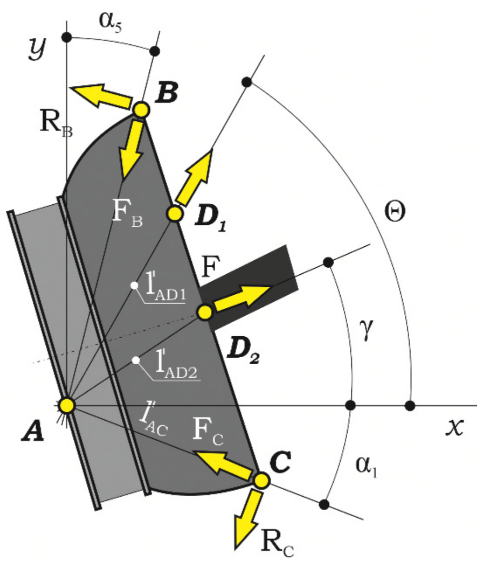


Figure 4: Calculation scheme for the distribution of forces behind the obturation line of a filtering respirator

Its solution will make it possible to determine the distribution of clamping forces along the obturation line of the filter respirator by **Equations 11** and **12**:

$$\sigma_B = \frac{R_B}{S_B} \qquad (11)$$

$$\sigma_C = \frac{R_C}{S_C} \qquad (12)$$

Where S_B and S_C are the area of contact zones around the nasal bridge and chin, m^2.

The dependence of the isolation coefficient on the tension forces of the head of the filtering respirator can be represented as **Equation 13**:

$$K_i = k_B (\Delta p)^{a-1} (d_B)^b R_f \qquad (13)$$

Where:

- k_B, a, b – constants determined experimentally and depending on the design of the obturator, the shape of the slots, the clamping forces of the head, and the flow regime;
- $d_в$ – size of the holes between the obturator and the face, m;
- b – coefficient of the mode of the air flow: 1 is taken for laminar, 1.5 – for transitive, and 2 – for turbulent;
- R_r – aerodynamic resistance of the filtering respirator (for this type of filtering respirators – 7000 Pa s/m^3);
- Δp – differential pressure across the filter respirator, Pa (is 95 Pa).

To determine the value of K_i, computer simulation and theoretical calculation have been carried out. The geometrical dimensions of the filter respirator of the "Shakhtar" model are: half-mask height H=0.0707 m; surface area S=314 cm^2; half-mask thickness L=10 mm; thickness of the filter material from which the filter is made is 4 mm; filter area S_f= 500 cm^2; inlet radius for inhalation R=25 mm; equivalent slot radius R_s = 0.05-0.9 mm; wind speed U_0 = 0.1 m/s; air suction speed through the hole simulating the nose is 4 m/s; total air flow is from 30 to 95 dm^3/min; filter resistance is 80 Pa. The filter permeability coefficient is calculated by **Equation 14**:

$$k = \frac{Q}{S_ф} \times \frac{L}{\Delta P} = \frac{0,001583}{0,05} \times \frac{0,005 \cdot 0.0000183}{80} = 3,375 \cdot 10^{-11}\ \text{m}^2. \qquad (14)$$

The reciprocal is the viscous resistance used in the filter respirator design model by **Equation 15**:

$$VR = \frac{1}{k} = 2,9 \cdot 10^{10},\ 1/\text{m}^2. \qquad (15)$$

The flow of the carrier medium is presented in the form of homogeneous and porous areas of laminar viscous gas flow (**Bhattacharyya et al., 2006**) by **Equations 16, 17** and **18**:

$$\frac{\partial u_r}{\partial r} + \frac{u_r}{r} + \frac{\partial u_x}{\partial x} = 0, \qquad (16)$$

$$\varepsilon^{-2} P\left(u_r \frac{\partial u_r}{\partial r} + u_x \frac{\partial u_x}{\partial x}\right) = \frac{\partial P}{\partial x} + \frac{\mu}{\varepsilon}\left(\frac{\partial^2 u_x}{\partial r^2} + \frac{1}{r}\frac{\partial u_r}{\partial r} + \frac{\partial^2 u_x}{\partial x^2}\right) - \varepsilon \frac{\mu}{k} u_x, \qquad (17)$$

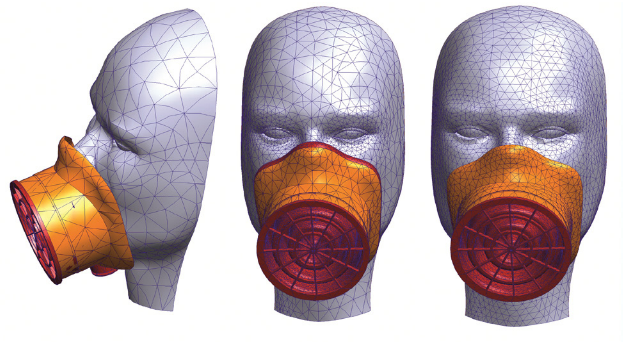
$$\varepsilon^{-2} P\left(u_r \frac{\partial u_r}{\partial r} + u_x \frac{\partial u_x}{\partial x}\right) = -\frac{\partial P}{\partial x} + \frac{\mu}{\varepsilon}\left(\frac{\partial^2 u_r}{\partial r^2} + \frac{1}{r}\frac{\partial u_r}{\partial r} - \frac{\partial^2 u_r}{\partial x^2}\right) - \varepsilon \frac{\mu}{k} u_r, \qquad (18)$$

Where:

- u_x, u_r – gas velocity components in a cylindrical coordinate system (x, r);

ε – filter porosity;
μ – coefficient of dynamic viscosity of air;
ρ – air density;
p – pressure;
k – porous medium permeability, m^2.

It was solved using the finite volume method in the environment of the "ANSYS" and "Solid works" packages. The calculation area outside and inside the porous zone was divided into unstructured quadrangular elements with a more thorough division at the boundary of the porous zone (see **Figure 5**).



a b c

Figure 5: Calculated area of the filtering respirator half mask: option 1 (a); option 2 (b); option 3 (c)

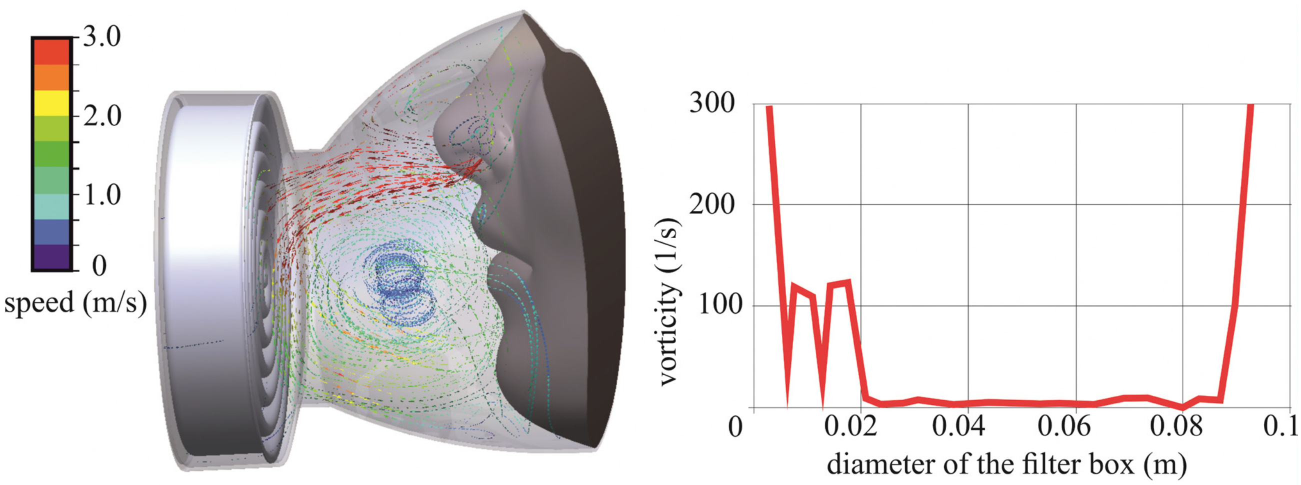
The Cauchy problem for **Equations 16, 17** and **18** in the found gas velocity field was solved by a numerical method based on the Runge-Kutta method (**Van-Huy et al., 2023**). At the first stage, the effect of the mesh size on the air flow through the filter and the slot was evaluated (see **Table 2**).

The values of the calculated gap areas were set in the range from 1 to 7 mm. The value of the coefficient of aspiration through the slot was calculated using the "CAE package". **Figures 6** and **7** show the streamlines and the distribution of air flow rates through the filter and slot at an air loss of 30 l/min, filter material permeability k = 9.55 × 10-11 m^2, and slot area S_l = 7 mm^2. It can be seen that the air passes into the submask space of the filtering respirator both through the filter and through the slot. As the resistance to the filter and the diameter of the hole increase, the amount of air that enters through the gap into the submask space of the filter respirator increases.

The determination of the coefficients k_B, a, b has been carried out in the Microsoft Office application "Excel". We can use the calculation of the production formula in the form of a Cobb-Douglas function, similar to the obtained dependence. To do this, we use the numerical values of the air flow through the slot, obtained by modelling in the "CAE package" with a change in the pressure drop across the filter and the slot diameter.

Table 2: Effect of mesh size on air flow through filter and slot

Model number	**Ratio of gap area to filter area S_a/S_f**					
	8×10^{-5} *variant 1*		**8×10^{-4} *variant 2***		**8×10^{-3} *variant 3***	
	number of nodes	***Qs*, l/min**	**number of nodes**	***Qs*, l/min**	**number of nodes**	***Qs*, l/min**
Model 1	260405	0.01434	103832	1.0374	140926	1.0398
Model 2	435148	0.01308	176706	1.0470	198703	1.0481
Model 3	613802	0.01284	392765	1.0470	420157	1.0494



a b

Figure 6: Interrelationship between flow vorticity and design parameters of a filtering half-mask: visualization of streamlines inside the half-mask when Q_f=30 l/min, S_s=7 mm^2, k=9.55×10^{-11} m^2 (a); dependence of the flow vorticity on the diameter of the filter box

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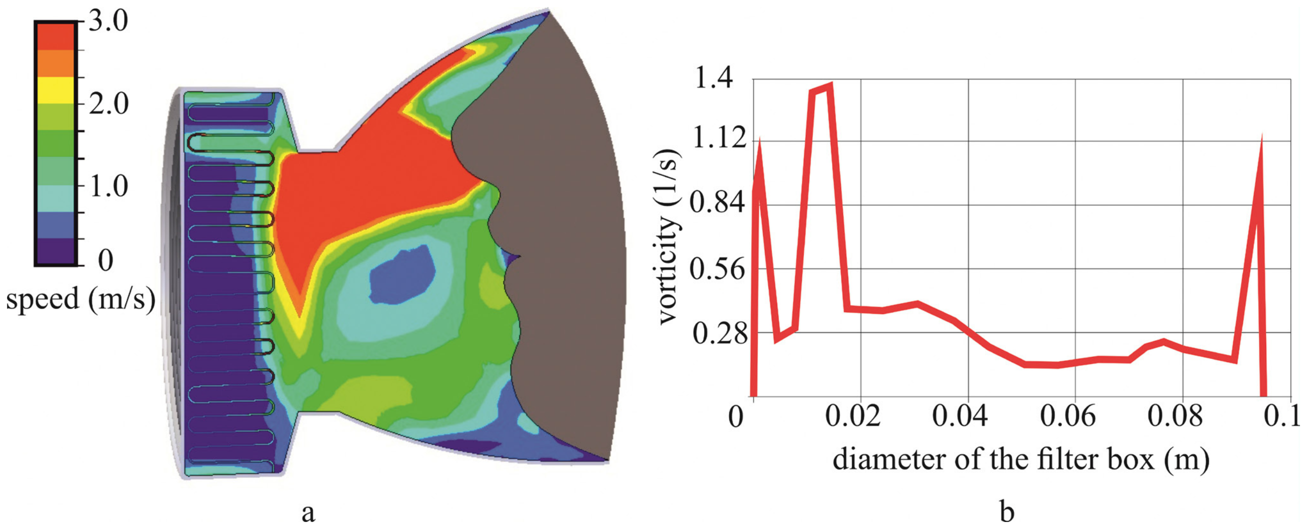

Figure 7: Interrelationship between airflow rate and filtering half-mask design parameters: visualization of airflow distribution inside the half-mask when Q_f=30 l/min, S_s=7 mm², k=9.55×10⁻¹¹ m² (a); dependence of the air flow rate on the diameter of the filter box (b)

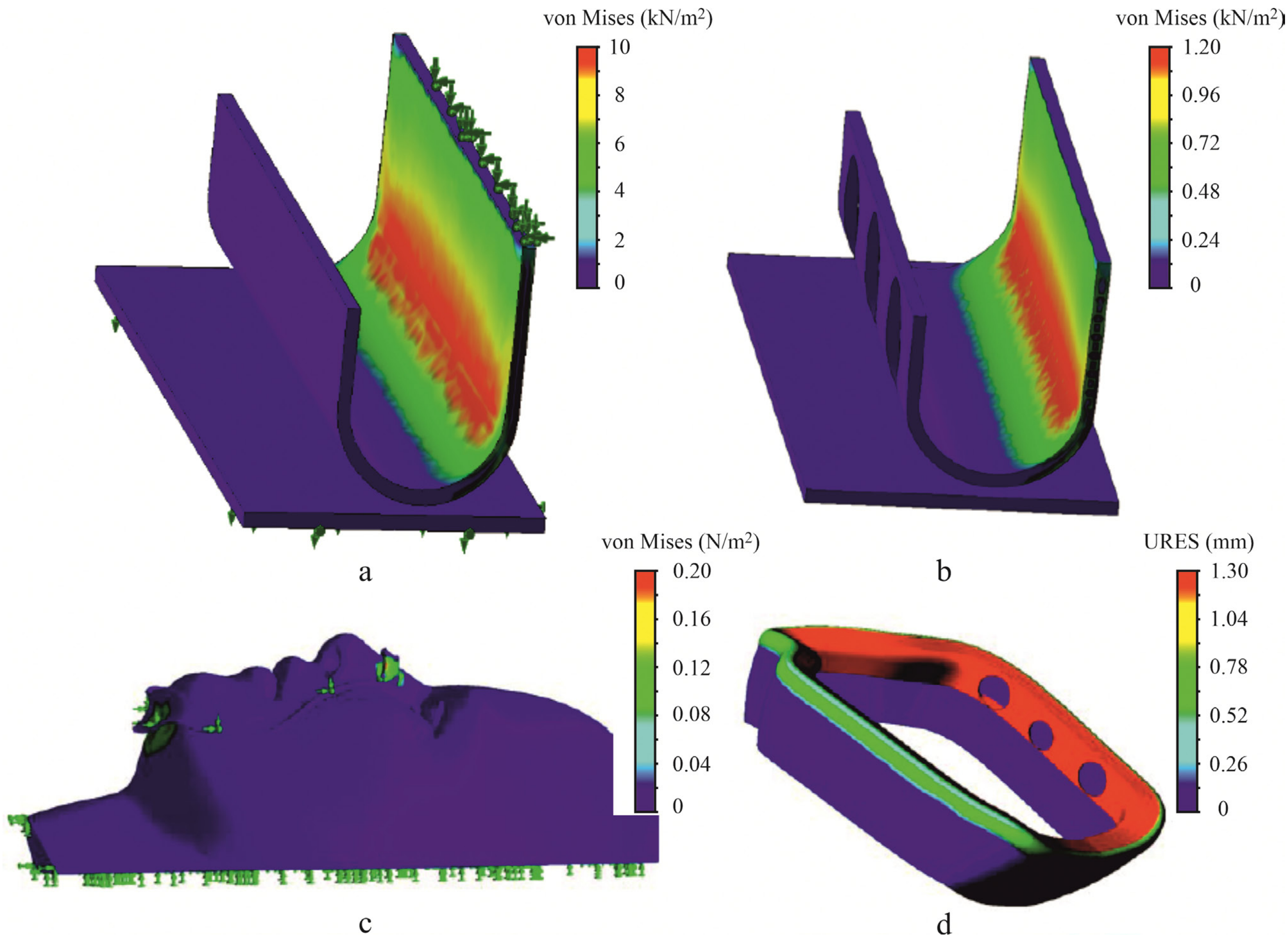

Figure 8: Distribution of forces along the obturation line of the filter respirator: non-perforated (a); perforated (b); on the calculation face model (c); on the calculation model of the respirator half-mask (d)

In the basic version, due to differences in the anthropometric characteristics of the faces of users, an uneven distribution of clamping forces occurs. This is due to the presence of leaks along the obturation line. Their elimination occurs if we increase the tension force of the headband bands of the filtering respirator which leads to an increase in clamping forces in the areas where the obturator is initially properly attached to the user's face (see **Fig-**

Table 3: The main geometric dimensions of the half-mask of a filter respirator

r_{AB}, mm	r_{AC}, mm	r_{AD1}, mm	r_{AD2}, mm	α_1, °	α_5, °
92	92	92	92	32	12

Table 4: Results of computer numerical simulation (fragment)

Variant number	Parameters								
	k_B, m^2	*a*, mm	D_1, mm	D_2, mm	*V*, unit	*F*, N	σ_B, kPa	σ_C, kPa	K_l, %
1	92	0.18	5	3	8	5	2.2	2.5	98.4
2	40	0.11	5	5	10	6	2.7	2.6	99.9
3	23	0.09	7	5	10	7	2.9	3.2	96.6

ure 8). At the same time, the presence of holes redistributes the clamping forces and ensures their uniformity.

The main geometric dimensions of the half-mask of a filtering respirator are presented in **Table 3**.

To determine the model with the best indicators of the distribution of clamping forces along the perimeter of the obturator, the corresponding simulation has been carried out in the "Toolbox MatLab-5.3.1" package, where a combined method for finding the extremum of the target function has been built, combining the "DFGS" algorithm and the projection method. The main modelling parameters are shown in **Table 2**. An acceptable result was considered to be a uniform distribution of clamping forces due to compensation for the diversity of anthropometric features by removing the bridges in the places where pressure is felt on the soft tissues of the face. A fragment of the results of computer numerical simulation using the above program is presented in **Table 4**.

As a result of processing expert assessments according to the described procedure, the following dependencies were obtained to determine the utility function of factors on their values:

$y = 1.863x^2 - 2.7227x + 1.0045$ – to estimate the mass of a filter respirator (r= 0.73);

$y = 0.4918x^2 - 1.2184x + 0.9778$ – to estimate the dimensions of the filter respirator (r= 0.76);

$y = 0.0083x^2 - 0.1633x + 0.8692$ – to assess the complexity of the filter respirator design (r= 0.82).

Where:

r – correlation coefficient.

After that, for each of the alternative options for a filtering respirator, the formula calculates the value of the total utility **Function 19**:

$$u\left(S_{j0}\right) = \sum_{q=1}^{k} \sum_{i=1}^{n} r_q w_{qi}^{j0} v_i, \qquad (19)$$

Where:

$r_q = 1$ – weight coefficient of the q^{th} operating mode of the filtering respirator ($k = 2$);

w_{qi}^{j0} – value of the utility function of a filtering respirator ($m = 5$, $k = 2$, $n = 3$);

v_i – weight coefficient of the i^{th} factor ($n = 3$).

The results of laboratory tests on six volunteers of this elastomeric half-mask of a filter respirator are shown in **Table 6**.

The difference in the values of the suction coefficients of one half-mask of a filtering respirator is due to the uneven distribution of clamping forces, which is facilitated by an increase in the distance between the centers of application of the normal and tangential components

Table 5: The results of calculating the value of the total utility function

Variant number	m / m_0	V / V_0	u_m	u_V	$u(S_j)$
1	1.00	1.000	0.14	0.15	0.20
2	0.16	0.006	0.62	0.97	0.72
3	0.13	0.010	0.68	0.96	0.54

Figure 9: Filtering respirator of the "Shakhtar" model with a perforated obturation strip

The calculated value of the total utility function with the following weight coefficients of partial quality criteria: mass - 0.6, dimension - 0.3, and design complexity - 0.1. The calculation results are shown in **Table 5**.

Results of laboratory research. To conduct laboratory studies to determine the suction coefficient, an elastomeric half-mask of a filtering respirator was made, corresponding to the parameters of model 3 (see **Figure 9**).

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Table 6: Results of an experimental study of an elastomeric half-mask of a filtering respirator

The tester	The value of the penetration coefficient of the half-mask of a filter respirator	The value of the coefficient of penetration of the test aerosol through a filter of the filter respirator	The value of the aerosol suction coefficient behind the obturation line of a filter respirator
1	1.3	0.9	0.4
2	1.5	0.8	0.7
3	1.4	0.9	0.5
4	1.6	0.8	0.8
5	1.8	1.2	0.6
6	1.6	1.1	0.5

of the clamping force F created by the headband of the half-mask (see **Figure 8**). An increase in the size of the plastic strip causes a significant moment M_F relative to the horizontal plane of the half-mask, which indicates the difference between the mechanical pressure in the area of the nasal bridge and the chin (see **Figure 10**).

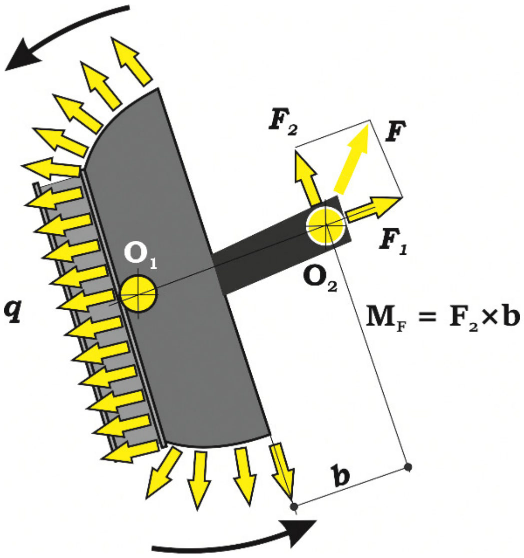

Figure 10: Distribution of forces on the half-mask of the filter respirator

It is the uneven distribution of clamping forces that leads to the appearance of leaks along the obturation line. The most likely place for suction in this half-mask is the mouth-nasal zone, where the pressure is less than 2 kPa, while to prevent the penetration of aerosol behind the obturation line, it is necessary to provide at least 2.5 kPa. It is possible to improve the insulating properties by increasing the tension of the headband, but this leads to an uncomfortable sensation, since the maximum pressure has already been fixed on the chin, which does not cause the formation of wrinkles on the face.

An additional important condition for ensuring uniform pressure along the obturation line of a filtering respirator is the location of the attachment of the headpiece on the half-mask. Experimental data show that the filter respirator number 3 has the best results. This is due to both the successful design of the obturator and the placement of the head attachment points.

So, the studies carried out made it possible to establish a relationship between the protection factor of a filtering respirator and their insulating properties. In particular, from the data in **Table 4** it can be seen that the best results are observed for sample 3. At the same time, the insulating properties of samples 1 and 2 also do not go beyond the range specified by regulatory documents.

Currently, "Shakhtar" respirators are being tested with the proposed solutions, including for miners. The test results are planned to be published by the authors in future papers.

4. Conclusions

Based on the results of theoretical modelling and laboratory tests, the effectiveness of the perforated obturator in the area of the nasal bridge, chin and cheeks has been determined by changing the size based on the anthropometry of the worker and increasing the comfort of using such structures throughout the entire production shift. At the same time, three variants of the perforated obturator of a filtering respirator have been considered: in the first one, the holes are made along the entire perimeter of the obturator; in the second, there are holes only in the area of the cheeks and nasal bridge; in the third, cutouts with a diameter of 5 mm are made in the area of the nasal bridge and cheeks. As a result of modelling a variety of alternative solutions, taking into account the protection factor of half-masks of a filtering respirator, the distribution of clamping forces determined in the environment of the "double-bladed packages, a rational design of a perforated obturator has been found (the second model). To prove the conclusions made, the total utility function of important factors has been established: the mass of the elastomeric half-mask, its dimensions and design complexity. Conducted laboratory studies to determine the coefficient of aerosol suction along the obturation strip showed the lowest penetration coefficient along the obturation strip in the second variant, which, according to the results of computer simulation, is 0.1%, while according to the experimental results, it ranged from 0.4 to 0.8%.

5. References

Ajith, M.M., Ghosh, A.K., and Jansz, J. (2020): Risk Factors for the Number of Sustained Injuries in Artisanal and Small-Scale Mining Operation. Safety and Health at Work, 11(1), 50-60. https://doi.org/10.1016/j.shaw.2020.01.001.

Akagi, F., Haraga, I., Inage, S.-I., and Akiyoshi, K. (2021): Effect of face shield design on the prevention of sneeze droplet inhalation. Physics Fluids, 33, 037131. https://doi.org/10.1063/5.0044367.

Akgün, M. (2015): Coal Mine Accidents. Turkish thoracic journal, 16(1), S1–S2. https://doi.org/10.5152/ttd.2015.008.

Alpert, S.I. (2020): The basic arithmetic operations with fuzzy numbers and the latest approaches to the application of the theory of fuzzy sets in the classification of space images. Mathematical Machines and Systems, 3, 49-59. https://doi.org/10.34121/1028-9763-2020-3-49-59.

Amponsah-Tawiah, K., and Mensah, J. (2016): Occupational Health and Safety and Organizational Commitment: Evidence from the Ghanaian Mining Industry. Safety and Health at Work. 7 (3), 225-230. https://doi.org/10.1016/j.shaw.2016.01.002.

Balan, V. (2021): Fuzzy modeling toolkit in strategic enterprise management. State and regions. Series: Economics and Business, 1(118), 48-56. https://doi.org/10.32840/1814-1161/2021-1-8.

Bazaluk, O., Cheberyachko, S., Cheberyachko, Y., Deryugin, O., Lozynskyi, V., Knysh, I., Saik, P., and Naumov, M. (2021): Development of a dust respirator by improving the half mask frame design. International Journal of Environmental Research and Public Health, 18, 5482. https://doi.org/10.3390/ijerph18105482.

Bazaluk, O., Ennan, A., Cheberiachko, S., Deryugin, O., Cheberiachko, Y., Saik, P., Lozynskyi, V., and Knysh, I. (2021): Research on Regularities of Cyclic Air Motion through a Respirator Filter. Applied Sciences, 11, 3157. https://doi.org/10.3390/app11073157.

Bhattacharyya, S., Dhinakaran, S., and Khalili, A. (2006): Fluid motion around and through a porous cylinder. Chemical Engineering Science, 61(13), 4451-4461. https://doi.org/10.1016/j.ces.2006.02.012.

Bulat, A., Dziuba, S., Minieiev, S., Koriashkina, L., and Us, S. (2020): Solution of the problem to optimize two-stage allocation of the material flows. Mining of Mineral Deposits, 14(1), 27-35. https://doi.org/10.33271/mining14.01.027.

Caggiari, S., Keenan, B., Bader, D.L., Mavrogordato, M.N., Rankin, K., Evans, S.L., and Worsley, P.R. (2022): A combined imaging, deformation and registration methodology for predicting respirator fitting. PLoS One, 17(11), e0277570. https://doi.org/10.1371/journal.pone.0277570.

Cai, M., Li, H., Shen, S., Wang, Y., and Yang, Q. (2018): Customized design and 3D printing of face seal for an N95 filtering facepiece respirator. Journal of Occupational and Environmental Hygiene, 15(3), 226-234. https://doi.org/10.1080/15459624.2017.1411598.

Cheberiachko, S., Yavorska, O., Deriuhin, O., and Yavorskyi, A. (2020): Evaluation of the probability of miners' protection while using filtering respirators. E3S Web of Conferences 201, 01021, 1-11. https://doi.org/10.1051/e3sconf/202020101021.

Cheberiachko, S.I., Yavorska, O.O., Yavorskyi, A.V., and Ikonnikov, M.Yu. (2022): A risk of pulmonary diseases in miners while using dust respirators. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, (5), 104-109. https://doi.org/10.33271/nvngu/2022-5/104.

Cheberyachko, S., Cheberyachko, Y., Naumov, M., and Deryugin, O. (2022): Development of an algorithm for effective design of respirator half-masks and encapsulated particle filters. International Journal of Occupational Safety and Ergonomics, 2(28), 1145-1159. https://doi.org/10.1080/10803548.2020.1869429.

Chopra, J., Abiakam, N., Kim, H., Metcalf, C., Worsley, P., and Cheong, Y. (2021): The influence of gender and ethnicity on facemasks and respiratory protective equipment fit: a systematic review and meta-analysis. BMJ Global Health, 6(11), e005537. https://doi.org/10.1136/bmjgh-2021-005537.

Cloet, A, Griffin, L, Yu, M. and Durfee, W. (2022): Design considerations for protective mask development: A remote mask usability evaluation. Appl Ergon. Jul, 102:103751. https://doi.org/10.1016/j.apergo.2022.103751.

Ennan, A.A., Abramova, N.M., Kuusk, V.M., and Shevchenko, T.M. (2006): Respirator. UA Patent No. 37959 C2. Kyiv: Ukrpatent.

Glass, D.C., Dimitriadis, C., Hansen, J., Hoy, R.F., Hore-Lacy, F., and Sim, M.R. (2022): Silica Exposure Estimates in Artificial Stone Benchtop Fabrication and Adverse Respiratory Outcomes. Annals of Work Exposures and Health, 66(1), 5-13. https://doi.org/10.1093/annweh/wxab044.

Holinko, V., Cheberiachko, S., Yavorska, O., and Radchuk, D. (2016): Study of protective properties of half-masks respirators used by miners. Mining of Mineral Deposits, 4, 29-36. https://doi.org/10.15407/mining10.04.029.

Ivaz, J. S., Stojadinović, S. S., Petrović, D. V., and Stojković, P. Z. (2021): A Retrospective Comparative Study of Serbian Underground Coalmining Injuries. Safety and health at work. 12 (4), 479–489. https://doi.org/10.1016/j.shaw.2021.07.004.

Jung, S., and Kim, J. (2020): Advanced Design of Fiber-Based Particulate Filters: Materials, Morphology, and Construction of Fibrous Assembly. Polymers (Basel), 12(8), 1714. https://doi.org/10.3390/polym12081714.

Kamaluddin, N.A., Kassim, M., and Shahbudin, S. (2022): A Review on 3D Augmented Reality Design Technique and Inward Leakage Testing on Protective Face Mask. Pertanika Journal of Science & Technology, 30(4), 2639-2658. https://doi.org/10.47836/pjst.30.4.19.

Klishch, I.M., Kovalchuk, A.O., Medvid, I.I., Pavlyshyn, A.V., and Klymnyuk, S.I. (2021): Comparative efficiency of the laminar pneumatic protection system for counteracting the penetration of bacterial agents. Achievements of Clinical and Experimental Medicine, 3, 100-103. https://doi.org/10.11603/1811-2471.2021.v.i3.12521.

Knobloch, J.K., Franke, G., Knobloch, M.J., Knobling, B., Kampf, G. (2023): Overview of tight fit and infection prevention benefits of respirators (filtering face pieces). Journal of Hospital Infection. https://doi.org/10.1016/j.ajic.2023.01.010.

Krishnan, U., Willeke, K., Juozaitis, A., Myojo, T., Talaska, G., and Shukla, R. (1994): Variation in quantitative respirator fit factors due to fluctuations in leak size during fit testing. American Industrial Hygiene Association journal, 55(4), 309–314. https://doi.org/10.1080/15428119491018943.

Kwon, Y.J., Kim, J.G., and Lee, W. (2022): A framework for effective face-mask contact modeling based on finite element analysis for custom design of a facial mask. PLoS One, 17(7), e0270092. https://doi.org/10.1371/journal.pone.0270092.

Lowney, C.J., Hsung, T.C., Morris, D.O., and Khambay, B.S. (2018): Quantitative dynamic analysis of the nasolabial complex using 3D motion capture: A normative data set. Journal of Plastic Reconstructive and Aesthetic Surgery, 71, 1332-1345. https://doi.org/10.1016/j.bjps.2018.05.001.

Mauricio da Costa Ramos, C., Roberto Lopes Dos Santos, J, and B Teixeira, R. (2022): Development of mask design as personal protective equipment through 3D printing. Materials Today: Proceedings, 70, 168-178. https://doi.org/10.1016/j.matpr.2022.09.016.

Myers, W.R., Allende, J.R., Iskander, W. and Stanley, C. (1988): Causes of in-Facepiece Sampling Bias - I. Half-Facepiece Respirators. The Annals of Occupational Hygiene. 32(3), 345–359. https://doi.org/10.1093/annhyg/32.3.345.

Nehrii, S., Nehrii, T., Volkov, S., Zbykovskyy, Y., Shvets, I. (2022): Operation complexity as one of the injury factors of coal miners. Mining of Mineral Deposits, 16(2), 95-102. https://doi.org/10.33271/mining16.02.095.

Nehrii, S., Nehrii, T., Zolotarova, O., Glyva, V., Surzhenko, A., Tykhenko, O., and Burdeina, N. (2022): Determining Priority of Risk Factors in Technological Zones of Longwalls. Journal of Mining and Environment, 13(3), 751-765. https://doi.org/10.22044/jme.2022.12142.2216.

Oestenstad, R.K. and Zwissler, A.M. (1991): A Comparison of Fit Provided by Natural and Silicone Rubber Facepieces of the Same Brand of Half-Mask Respirator. Applied Occupational and Environmental Hygiene, 6:9, 785-789.

Oestenstad, R.K., Dillion, H.K. and Perkins, L.L. (1990): Distribution of face seal leak sites on a half-mask respirator and their association with facial dimensions. Am Ind Hyg Assoc J., 51(5), 285-290. https://doi.org/10.1080/15298669091369664

O'Kelly, E., Arora, A., Pirog, S., Ward, J., and Clarkson, P.J. (2022): Experimental Measurement of the Size of Gaps Required to Compromise Fit of an N95 Respirator. Disaster Medicine and Public Health Preparedness, 21, 1-13. https://doi.org/10.1017/dmp.2022.23.

Olizarenko, S., Samokish, A., and Kapranov, V. (2018): Method of comparison of the degree of excessity between the fuzzy sets of type 1 and interval fuzzy sets. Systems of Arms and Military Equipment, 2(54), 136-141. https://doi.org/10.30748/soivt.2018.54.19.

Shaffer, R.E., and Janssen, L.L. (2015): Selecting models for a respiratory protection program: What can we learn from the scientific literature? American Journal of Infection Control, 43, 127-132. https://doi.org/10.1016/j.ajic.2014.10.021.

Shenal, B.V., Radonovich, L.J., Jr, Cheng, J., Hodgson, M. and Bender, B.S. (2012): Discomfort and exertion associated with prolonged wear of respiratory protection in a health care setting. Journal of occupational and environmental hygiene, 9(1), 59–64. https://doi.org/10.1080/15459624.2012.635133.

Stemen, D., Ge, M., Hwang, D., Qaddoumi, B., Roden, M., Nanda, N., and Ference, E. (2021): Frame to Improve the Fit of N95 Filtering Face Mask Respirators. Journal of Occupational and Environmental Medicine, 63(6), e362-e366. https://doi.org/10.1097/JOM.0000000000002223.

Strzemecka, J., Goździewska, M., Skrodziuk, J., Galińska, E.M., and Lachowski, S. (2019): Factors of work environment hazardous for health in opinions of employees working underground in the 'Bogdanka' coal mine. Annals Agricultural and Environmental Medicine, 26(3), 409-414. https://doi.org/10.26444/aaem/106224.

Tarfaoui, M., Nachtane, M., Goda, I., Qureshi, Y., and Benyahia, H. (2020): 3D printing to support the shortage in personal protective equipment caused by COVID-19 pandemic. Materials, 13, 3339. https://doi.org/10.3390/ma13153339.

Van-Huy, V., Kikuchi, M., and Kubota, H. (2023): Shaping a New Level of Bus Service under a Novel Concept of Bus Interaction: A Meta-Review. Journal of Transportation Technologies, 13, 173-207. https://doi.org/10.4236/jtts.2023.132009.

Verma, S., and Chaudhari, S. (2017): Safety of Workers in Indian Mines: Study, Analysis, and Prediction. Safety and Health at Work. 8 (3), 267-275. https://doi.org/10.1016/j.shaw.2017.01.001.

Vinothkumar, N., and Varatharasan V. (2017): CFD flow simulation of protection layer in air pollution mask. International Journal of Advanced Research in Basic Engineering Sciences and Technology, 3(24), 198-304. https://doi.org/10.20238/IJARBEST.2017.03s24030031.

Wardhan, R., Brennan, M.M., Brown, H.L., Creech, T.B. (2019): Does a Modified Adhesive Respirator Improve the Face Seal for Health Care Workers Who Previously Failed a Fit Test?: A Pilot Study During the Coronavirus Disease. Pandemic. A&A practice, 14(8), e01264. https://doi.org/10.1213/XAA.0000000000001264.

Wei-ci, G., and Chao, W. (2011): Comparative Study on Coal Mine Safety between China and the US from a Safety Sociology Perspective. Procedia Engineering, 26, 2003-2011. https://doi.org/10.1016/j.proeng.2011.11.2397.

Wetherell, A., Brown, J., Dennis, M., Mathers, G., Nightingale, J., Rowbotham, A., Slater, A., Thompson, D., Weir, J., Williams, G. (2001): The Replacement General Service Respirator: a technology demonstration programme to evaluate candidate technologies. Report Dstl/TR/02269. London, 126 p.

Wu, B., Leppänen, M., Yermakov, M., and Grinshpun, S.A. (2017): Evaluation of a New Instrument for Aerosol Quantitative Fit Testing. International Society for Respiratory Protection Journal of the International Society for Respiratory Protection, 34(2), 111-127.

SAŽETAK

Povećanje izolacijskih svojstava filtarskih respiratora za zaštitu dišnih organa rudara od prašine

Kako bi se povećala izolacijska svojstva elastomernih polumaski, predlaže se perforacija brtve u području hrpta nosa, brade i obraza, što omogućuje promjenu njezine veličine i sprječava pojavu bora na licu korisnika na mjestima gdje su specifične značajke lica određenoga korisnika. Predložene su tri inačice perforiranih brtvi filtarskoga respiratora: u prvoj su rupe napravljene po cijelome obodu brtve, u drugome su rupe samo u području obraza i nosnoga mosta, a u trećemu se rade rezovi promjera 5 mm u području nosnoga hrpta i obraza. Alternativna rješenja razvijena su temeljem glavnih pokazatelja dobivenih modeliranjem u programskim paketima „ANSYS" i „Solid works", uzimajući u obzir koeficijent zaštite filtarskoga respiratora polumaski, raspodjelu tlačnih sila. Za donošenje odluke o odabiru najboljega modela dodatno su u obzir uzeti: masa elastomerne polumaske, njezine dimenzije i složenost dizajna. Na temelju ekspertne ocjene, prema opisanome postupku određivanja funkcije korisnosti faktora iz njihovih vrijednosti, utvrđeno je da drugi model polumaske karakteriziraju najbolji parametri. Provedene laboratorijske studije za određivanje koeficijenta apsorpcije aerosola linijom začepljenja pokazale su najniže vrijednosti u drugoj inačici.

Ključne riječi:
zaprašenost radnoga prostora, profesionalna bolest, filtarski respirator, antropometrijski parametri lica, parametri respiratora

Authors' contribution

Serhii Cheberiachko (doctor of technical sciences, professor): initiated the idea, developed a methodological approach, established dependencies and criteria, lead the whole process and supervised it from the beginning to the end. **Yuriy Cheberiachko** (doctor of technical sciences, professor): initiated the idea, developed a methodological approach, established dependencies and criteria. **Oleg Deryugin** (PhD, associate professor): analyzed literary sources, processed and analyzed the results, constructed graphs. **Bohdan Kravchenko** (graduate student): processed the results. **Tetiana Nehrii** (PhD, associate professor): reviewed the article, completed the literature review, analyzed the results. **Serhii Nehrii** (doctor of technical sciences, professor): analyzed the literary sources of information, the general edition of the article, constructed graphs. **Oksana Zolotarova** (PhD, associate professor): submitted and reviewed the paper.

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